

A Search for Simultaneous Optical Counterparts of Gamma-Ray Bursts

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Final Report

Abstract

Gamma Ray Bursts (GRBs) are brief, randomly located, releases of gamma-ray energy from unknown celestial sources that occur almost daily. The study of GRBs has undergone a revolution in the past three years due to an international effort of follow-up observations made possible by the instantaneous distribution of reliable GRB coordinate information over the internet provided by NASA's GCN (GRB Coordinates Network). The 3-year LDRD project described here, done in collaboration with the workers responsible for the GCN, was the very first serious system to actively utilize the GCN and thus played a major role in the development of the GCN and the dramatic increase in our understanding of GRBs.

The scientific objective of this project was to measure the intensity of any prompt visible radiation accompanying the gamma-ray emission utilizing a small but sensitive robotic telescope that responded to GCN triggers by rapidly taking images of the GCN error box. The instrument developed for this project, LOTIS, was the first of its kind, and the longest running, collecting data on over 75 GRBs during its 3 year running period. The results of LOTIS and the other follow-up programs have now shown that GRBs are at cosmological distances and interact with surrounding material as described by the "fireball model." Visible, prompt, optical counterparts have only been seen in one case and are therefore very rare or much dimmer than the sensitivity of the current instruments. This places numerical limits on the surrounding matter density, and other physical parameters in the GRB environment. A much more sensitive instrument, Super-LOTIS, has been developed for operation at Kitt-Peak.

This project has resulted in over 10 publications and one Ph. D. thesis.

Introduction

The dramatic breakthrough in our understanding of GRBs occurred when the high resolution x-ray detector on the Beppo-Sax satellite was able to determine the position of a GRB with sufficient accuracy to enable a large telescope to observe a faint, fading afterglow days later. Optical and radio

afterglows now have been observed for about a dozen GRBs during the last two years. These long-lasting but faint afterglows have been successfully explained in the “fireball models” as the result of the heating up of surrounding material by the GRB energy release. From the spectra of the apparent hosts of the afterglows we now know that the GRBs are at cosmological distances and have some understanding of energy output, ambient environment, and dynamics.

The goal of this experiment is to measure prompt visible emission occurring within seconds of the gamma ray energy release and presumably containing information about the GRB progenitor. To accomplish this we developed and have been operating an automated wide field-of-view telescope for over 3 years at Lawrence Livermore National Laboratory (LLNL) that responds to “triggers” distributed by the Gamma-ray burst Coordinate Distribution Network (GCN) by rapidly imaging the GRB coordinate error boxes. This instrument collected data on over 75 GRBs and in all cases found no evidence for prompt visible emission down to its sensitivity limit.

A competing instrument having similar sensitivity recently began operation at Los Alamos National Laboratory during the onset of the rainy season in Livermore when LOTIS is usually shut down. During this time the instrument at Los Alamos responded to a GCN trigger from GRB990123 which on subsequent analysis of the resulting images was seen to have a prompt optical transient at magnitude $V \sim 9$. A signal this bright would clearly have been seen by LOTIS, however to this date prompt optical signals have not been seen from any other GRB in the large LOTIS sample. GRB990123 was also unusual in terms of its total x-ray fluence, peak flux and spectrum.

We now describe the LOTIS and Super-LOTIS system and the results from these experiments.

LOTIS

LOTIS was constructed to respond rapidly to real-time GRB triggers provided by the GCN (GRB Coordinates Network). Covering the large real-time GCN trigger error box, which is limited by the BATSE detector on CGRO to have a 1σ error of $2\sim 10^\circ$, requires wide field-of-view optics to obtain statistically meaningful results. LOTIS utilizes commercially available Canon f/1.8 telephoto lenses, which have short, 200 mm focal lengths, and effective apertures of 110 mm diameter. The electronic focal plane sensors are 2048 x 2048 pixel Loral 442A CCDs with $15\text{ }\mu\text{m} \times 15\text{ }\mu\text{m}$ pixels driven

by custom read-out electronics. The read-out clock rate is 500 kHz, which results in an image read-out time of ~ 8 sec. Each Canon telephoto lens/camera assembly has a field-of-view of $8.8^\circ \times 8.8^\circ$ with a pixel scale of 15 arcsec. Four cameras are arranged in a 2×2 array to cover a total field-of-view of $17.4^\circ \times 17.4^\circ$ overlapping 0.2° in each dimension. LOTIS is located at Site 300, LLNL's remote test facility, 25 miles east of Livermore, California. The first picture of Figure 1 shows the LOTIS system.

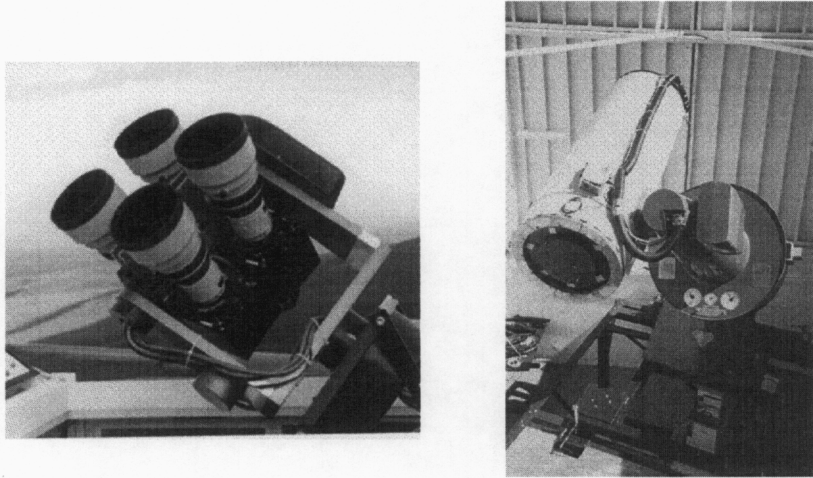


Figure 1. LOTIS and Super-LOTIS Telescopes

LOTIS Results

During more than 1330 possible nights of observations (Oct. 1996 through May 2000), LOTIS responded to 145 GCN triggers. Of these, 75 triggers were unique GRB events. The quality of the LOTIS "coverage" for a given event depended on: the observing conditions, the LOTIS response time, the error in the rapidly distributed GRB coordinate, the size of the final error box, and the duration of the GRB. The following table lists the 13 events for which LOTIS achieved the best overall coverage. These results have been published (See the publication list).

Table 1 shows our best events during this period. Since LOTIS did not see any optical activity in the visible, correlated with any of these events, we determine from the conditions in each case an *upper limit* on the brightness of any possible visible signal missed by LOTIS.

This set of LOTIS upper limits has been used to determine if typical GRBs, for which LOTIS has shown not to have counterparts, are similar to

GRB990123, the only GRB event ever observed to have a prompt visible counterpart. Since GRB990123 also had an unusually strong gamma ray emission, it is interesting to compare the LOTIS limits with predicted optical signals based on the measured optical intensity of GRB990123 scaled by the ratio of the x-ray intensity for each LOTIS burst to the x-ray intensity of GRB990123. Since the x-ray intensity of a burst can be quantified by its peak flux and/or its total fluence we present predictions for both in the last 2 columns of Table 1. When we compare these results with the LOTIS limiting magnitude in the column 5, we find that the predicted prompt optical signals are in most cases brighter than the LOTIS upper limits (especially after GRB 970919 when LOTIS was upgraded). This suggests that GRB990123 was not a typical GRB.

Event	Peak Flux ($\gamma\text{cm}^{-2}\text{s}^{-1}$)	Fluence (ergcm^{-2})	Burst Duration (sec)	LOTIS Response Time (sec)	LOTIS Limit	Scaled Mag to Peak Flux	Scaled Mag to Fluence
961017	1.98	5.07	1.2	11.0	11.5	11.3	15.9
961220	1.60	18.11	9.8	9.0	11.5	11.5	14.5
970223	16.84	968.	16.3	11.5	11.0	9.0	10.2
970714	1.32	17.09	2.0	14.1	11.3	11.7	14.6
970919	0.77	22.49	20.9	11.8	11.5	12.3	14.3
971006	1.79	258.	48.1	17.1	12.1	11.4	11.7
971227	2.11	9.25	6.8	10.0	12.3	11.2	15.3
990129	4.99	585.	200.	140.8	14.5	10.3	10.8
990308	1.26	164.	50.	132.1	13.5	11.8	12.2
990316	3.67	529.	40.	13.6	14.3	10.6	10.9
990413	2.57	68.13	15.	13.0	14.0	11.0	13.1
990803	12.19	1230.	28.	15.0	14.5	9.3	10.0
990918	3.17	25.21	6.5	8.3	14.3	10.8	14.2

Table 1. Best LOTIS events and scaled GRB990123 limits

The LOTIS results have also been used by Sari & Piran to constrain their external-reverse-shock GRB model. This model assumes that the fraction of the GRB energy emitted in the optical band depends on the values of the cooling frequency and the characteristic synchrotron frequency. For the external reverse shock these frequencies are given by

$$\begin{aligned}
 \nu_c &= 8.8 \times 10^{15} \text{ Hz} \left(\frac{\epsilon_B}{0.1} \right)^{-3/2} E_{52}^{-1/2} n_1^{-1} t_A^{-1/2} \\
 \nu_m &= 1.2 \times 10^{14} \text{ Hz} \left(\frac{\epsilon_e}{0.1} \right)^2 \left(\frac{\epsilon_B}{0.1} \right)^2 \left(\frac{\gamma_0}{300} \right)^2 n_1^{1/2}
 \end{aligned}$$

where ϵ_e and ϵ_B are the fraction of equipartition energy in the electrons and magnetic field, E_{s2} is the total energy in units of 10^{52} erg, n_1 is the density of the surrounding matter in cm^{-3} , γ_0 is the initial Lorentz factor, and t_A is the duration of the emission in seconds. Assuming that the observable parameters of the total fluence and the observation time are fixed at $S=2.33 \times 10^{-7} \text{ erg cm}^{-2}$ and $t_A=10 \text{ sec}$, respectively, we can predict prompt optical emission at different values of the parameters used in the Sari & Piran model. These predicted contour lines are shown in Figure 2. The darker regions in these plots are the likely gamma-ray burst production environment. From this analysis LOTIS results imply that the GRBs are created at low surrounding matter density, high initial Lorentz factors, low equipartition energy in the magnetic field, and high equipartition energy in the electron.

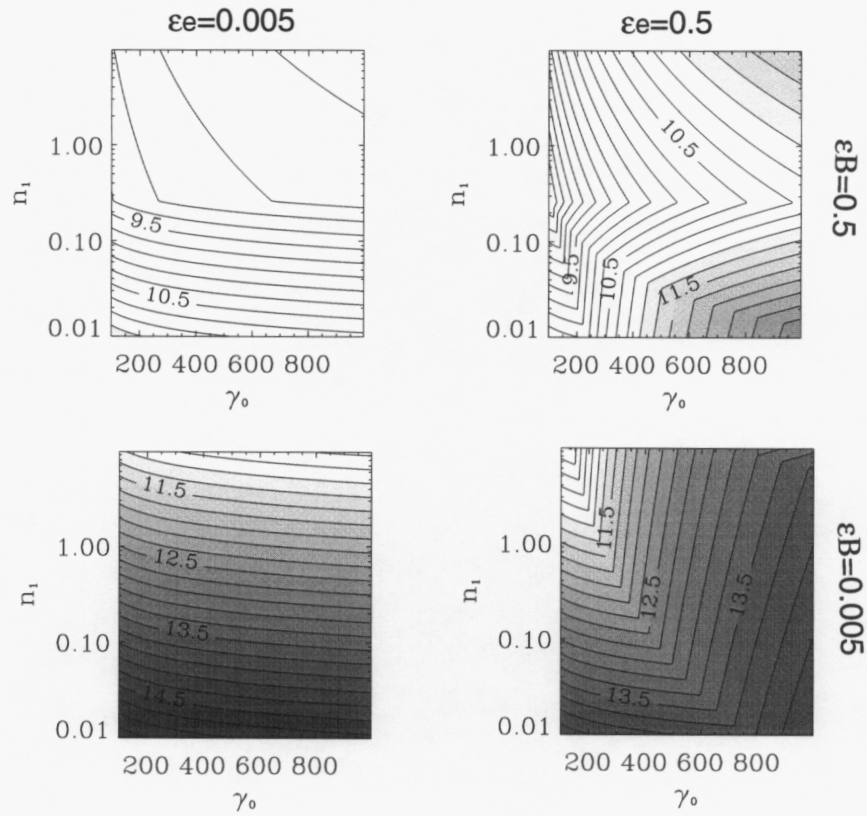


Figure 2. LOTIS constraints on GRB production parameters. The darker regions are preferred by LOTIS.

Super-LOTIS

Super-LOTIS is a next-generation system designed to be sensitive enough to detect the optical levels predicted by current theories. The telescope is a Boller and Chivens 0.6 meter reflective telescope of f/3.5. The second panel of the Figure 1 shows the telescope. We automated the telescope for GRB follow-up work by adding computer controllable drives. These drives can point to any part of the sky within 30 sec upon receipt of a GCN trigger. We also designed and fabricated a custom 4-element coma corrector to match the point spread function to the pixel scale at the corners of the imaging CCD. The sensor is a LOTIS CCD camera utilizing a Loral 442A 2048 x 2048 CCD (15 μ m x 15 μ m pixels) with LLNL built readout electronics. The CCD has thermo electric cooling (to -30°C) to minimize dark current and readout noise. Super-LOTIS has a 0.84° x 0.84° field-of-view (1.5 arcsec/pixel) sufficient to cover the error boxes expected from upcoming GRB satellite missions whose triggers will be distributed by the GCN.

Our data acquisition system includes custom readout electronics, a custom hardware power control unit, a weather station and a housing control unit. Extensive on-line scheduling software has been written to handle various triggers. Priority is given to the most recent trigger that has smallest error box. Our scanning strategy and automation allows us to record GRB optical activity as early as 30 sec.

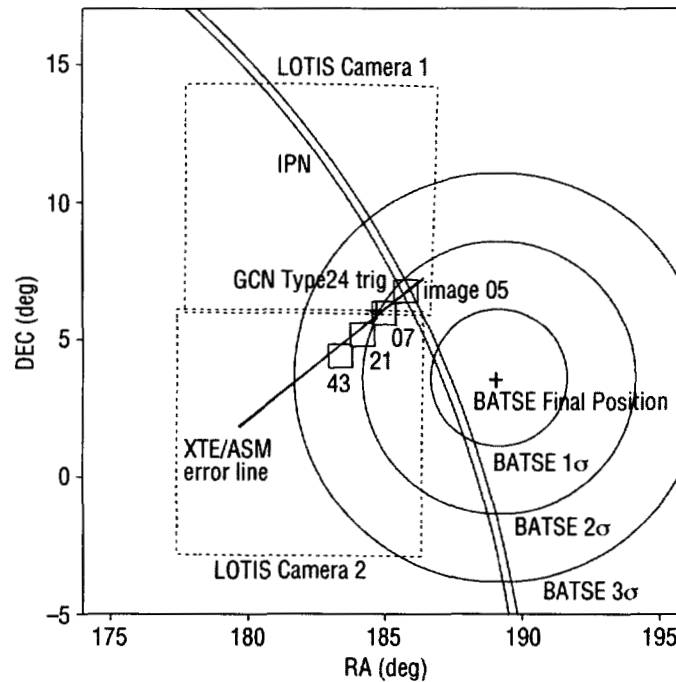
In April 2000, we moved the Super-LOTIS telescope to the Kitt Peak National Observatory and are ready to receive real-time GRB coordinates from the HETE satellite which is scheduled for launch in October 2000.

Super-LOTIS Response to a GRB trigger

While we were integrating the telescope system in Livermore, Super-LOTIS obtained an early time observation of the error box of GRB 990308. This event was detected and localized by the XTE/All-Sky Monitor. Super-LOTIS began a raster scan around the BATSE GCN coordinates 1700 sec after the start of the burst. Four Super-LOTIS images (30 sec integration; t=1694 sec, 1809 sec, 2620 sec, 3923 sec) covered most of the XTE/ASM error box within the BATSE 2 σ error circle.

The coverage of this event is shown in Figure 3. In this figure the circles represent the BATSE 1 and 3 σ errors; the arc represents the IPN error, and the thin line represents the XTE observation. The large boxes represent the coverage of LOTIS images of this event at 132 s after the

burst; and the small boxes are the coverage of Super-LOTIS images taken during the raster scan. We searched for optical transients in the area where the error boxes overlap. Even though an optical afterglow for this event had been reported at 3.28 and 3.47 hr after the burst, Super-LOTIS detected no fading or flaring objects brighter than $V > 15.3$ at 28.2 minutes. The poor observing conditions and the usage of an uncooled prototype CCD camera at the time prevented us from reaching deeper limits.



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Figure 3. LOTIS and Super-LOTIS coverage of GRB990308 event.

Achievements

We successfully constructed the LOTIS and Super-LOTIS systems which are automated and dedicated for follow-up observations of the GRBs. These systems are the fastest and the most sensitive GRB follow up systems available in the world as of August 2000. Our LOTIS results are published in many scientific journals and quoted in many papers. One graduated student, George Williams from Clemson University, obtained his Ph. D. from the LOTIS experiment.

With the LOTIS and Super-LOTIS systems, we will be able to cover GRB optical activity from 10 sec to many hours to a magnitude level of $V \sim 14$ -

19. With HETE and other prompt GRB coordinate distributing satellites, we will be able to measure early time optical activity. Once we detect an optical transient, we will also be able to promptly alert other telescopes.

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